

# $Z'$ -mediated Supersymmetry Breaking

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We consider a class of models in which supersymmetry breaking is communicated dominantly via a  $U(1)'$  gauge interaction, which also helps solve the  $\mu$  problem. Such models can emerge naturally in top-down constructions and are a version of split supersymmetry. The spectrum contains heavy sfermions, Higgsinos, exotics, and  $Z' \sim 10 - 100$  TeV; light gauginos  $\sim 100 - 1000$  GeV; a light Higgs  $\sim 140$  GeV; and a light singlino. A specific set of  $U(1)'$  charges and exotics is analyzed, and we present five benchmark models. Implications for the gluino lifetime, cold dark matter, and the gravitino and neutrino masses are discussed.

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## I. INTRODUCTION AND MOTIVATION

To a large extent, the mediation mechanism of supersymmetry (SUSY) breaking determines the low energy phenomenology. A well-studied scenario is gravity mediation [1]. During the last couple of decades, in order to satisfy the increasingly stringent constraints from flavor changing neutral current measurements, many other mediation mechanisms, such as anomaly mediation [2], gauge mediation [3], and gaugino mediation [4], have been proposed (for a review, see [5]). In this letter, we present an alternative mechanism in which SUSY breaking is mediated by exotic gauge interactions, such as an additional  $U(1)'$ . Concrete superstring constructions frequently lead to additional, non-anomalous,  $U(1)'$  factors in the low-energy theory (see, e.g., [6]) with properties allowing a  $U(1)'$ -mediated SUSY breaking. Scenarios with an extra  $U(1)'$  involved in supersymmetry breaking mediation have been studied in various contexts [7]. Here, we study a new scenario where  $Z'$ -mediation is the dominant source for both scalar and gaugino masses.

Another ingredient we would like to consider is the  $\mu$ -problem of the Minimal Supersymmetric Standard Model (MSSM). One class of solutions invokes a spontaneously broken Peccei-Quinn symmetry (see, e.g., [8]). From the point of view of top-down constructions it is common that such a symmetry is promoted to a  $U(1)'$  gauge symmetry [9]. Identifying this  $U(1)'$  with the mediator of SUSY breaking sets  $\mu$  (as well as  $\mu B$ ) to the scale of the other soft SUSY breaking parameters, which are of the right size whether or not the electroweak symmetry breaking is finely tuned.

In the setup we propose, schematically shown in Fig. 1, visible and hidden sector fields do not have direct renormalizable coupling with each other. At the same time, they are both charged under  $U(1)'$ . A supersymmetry breaking  $Z'$ -ino mass term,  $M_{\tilde{Z}'}$ , is generated due to the  $U(1)'$  coupling to the hidden sector. The observable sector fields feel the supersymmetry breaking through their couplings to  $U(1)'$ . The sfermion masses are of order  $m_f^2 \sim M_{\tilde{Z}'}^2/16\pi^2$ . The  $SU(3)_C \times SU(2)_L \times$

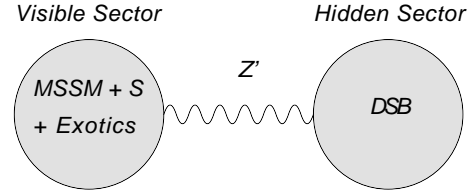


FIG. 1:  $Z'$ -mediated supersymmetry breaking.

$U(1)_Y$  gaugino masses are generated at higher loop order,  $M_{1,2,3} \sim M_{\tilde{Z}'} / (16\pi^2)^2$ , which is 2-3 order of magnitudes lighter than the sfermions. LEP direct searches suggest electroweak-ino masses  $> 100$  GeV. We therefore expect that the sfermions are heavy, typically about 100 TeV. In this sense, this scenario can be viewed as a mini-version of split-supersymmetry [10]. In particular, one fine-tuning is needed to maintain a low electroweak scale. This scenario does not have flavor or CP violation problems due to the decoupling of the sfermions. One important difference from split-supersymmetry is the  $\mu$ -parameter, which is set by the scale of  $U(1)'$  breaking.

## II. GENERIC FEATURES OF $Z'$ -MEDIATED SUPERSYMMETRY BREAKING

The visible sector contains an extension of the MSSM. First, we introduce an extra  $U(1)'$  gauge symmetry. Second, the  $\mu$  parameter is promoted into a dynamical field,  $\mu H_u H_d \rightarrow \lambda S H_u H_d$ .  $S$  is a Standard Model singlet which is charged under the  $U(1)'$ . Third, we include exotic matter multiplets with Yukawa couplings to  $S$ ,  $\sum_{i \in \{\text{exotics}\}} Y_i S X_i X_i^c$ . They are included to cancel the anomalies associated with the  $U(1)'$ . Such exotics and couplings generically exist in string theory constructions.



	1	2	3	4	5
$Q_2$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{2}$	$-\frac{1}{2}$
$Q_Q$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2}$
$g_{z'}$	0.45	0.23	0.23	0.06	0.04
$\lambda$	0.5	0.8	0.8	0.3	0.3
$Y_D$	0.6	0.7	0.8	0.4	0.6
$Y_E$	0.6	0.6	0.6	0.1	0.1
$\langle S \rangle$	$2 \times 10^5$	$7 \times 10^4$	$6 \times 10^4$	$2 \times 10^5$	$8 \times 10^4$
$\tan \beta$	20	29	33	45	60
$M_1$	2700	735	650	760	270
$M_2$	710	195	180	340	123
$M_3$	4300	1200	1100	540	200
$m_H$	140	140	140	140	140
$m_{\tilde{Q}_3}$	$10^5$	$5 \times 10^4$	$4 \times 10^4$	$8 \times 10^4$	$4 \times 10^4$
$m_{\tilde{L}_3}$	$3 \times 10^5$	$10^5$	$10^5$	$2 \times 10^4$	$10^5$
$m_{3/2}$	890	3600	810	3	0.1
$m_{\tilde{S}}$	4300	230	160	31	4
$m_{Z'}$	$7 \times 10^4$	$1.5 \times 10^4$	$1.3 \times 10^4$	5600	2100

TABLE I: Model inputs and superpartner spectrum of five representative models. Masses are in GeV. We fix  $M_{Z'} = 10^6$  GeV. The masses of the first two generations of squarks and sfermions are typically larger than that of the third. The input parameters  $\lambda$ ,  $g_{z'}$  and  $Y_{D,E}$  are defined at  $\Lambda_S$ . The spectra are calculated using exact Renormalization Group Equations (RGE) (see, e.g., [12]). There is a theoretical uncertainty due to multiple RGE thresholds. This mainly affects  $m_H$ , leading to a several GeV uncertainty. The gravitino mass is calculated by  $m_{3/2} = \Lambda_S^2/M_P$  assuming  $\Lambda_S \sim \sqrt{F}$ . There could be deviations from this relation in some SUSY breaking models which could lead to a gravitino mass that is different by up to a couple orders of magnitude (typically lower). For details, see [11].

choices of charges and other parameters.  $U(1)'$  has to be spontaneously broken by radiative corrections. It must allow appropriate fine-tuning to break the electroweak symmetry. Moreover, since  $U(1)'$   $D$ -terms could contribute to scalar masses with either sign, one must check for the existence of charge or color breaking minima.

We have found several regions in the  $(Q_Q, Q_2)$  space where a solution satisfies all the constraints. A detailed scan will be presented in a forthcoming publication [11]. The results exhibit a variety of patterns for the low energy spectrum. In Table I, we display five representative models. Different ordering of the MSSM gaugino and singlino masses could give rise to very different phenomenology. The singlino mass typically has more variation since it is determined by fine-tuning. The appearance of a light  $Z'$  in the spectrum, shown in model 5 (with  $\sigma \times \text{BR}(Z' \rightarrow \ell\bar{\ell}) \gtrsim 10$  fb), could result in a spectacular signal and help untangle the underlying model. This generically happens in the case where the singlino is very light.

A wino as the lightest supersymmetric particle (LSP) and its nearly degenerate charged partner (the degeneracy is lifted at one-loop by about 160 MeV [13] and allows the decay  $\tilde{W}^+ \rightarrow \tilde{W}^0 + \pi^+$ , which results in a 4 cm displaced vertex) have been studied extensively [14], especially in connection with anomaly mediated models [2].

It can annihilate efficiently into gauge bosons. For pure thermal production the dark matter density is too low for the several hundred GeV mass range we have assumed. However, it can be considerably larger for non-standard cosmological scenarios.

Due to small mixings, at most of the order  $\lambda v/\mu \tan \beta$ , the decay chain involving the singlino and wino will have a long life-time which could result in a displaced vertex. For example, depending on whether the decay is two or three-body, the life-time for  $\tilde{S} \rightarrow h^{(*)} + \tilde{W}$  or  $\tilde{W} \rightarrow h^{(*)} + \tilde{S}$  is in the range of  $10^{-11} - 10^{-19}$ s. This could give an interesting signature in case of  $M_2 > M_{\tilde{S}}$ , or  $M_{\tilde{S}} > M_2$  if the  $Z'$  is light enough and has an appreciable branching ratio for decay into the singlino.

There is a wide range of possible gravitino masses,  $m_{3/2} \sim 10^{-3} - 10^4$  GeV. With typical assumptions about cosmology,  $m_{3/2}$  is strongly constrained by Big Bang Nucleosynthesis (BBN). If the gravitino is not the LSP, we typically require either it to be heavy ( $> 10$  TeV) so it decays before BBN, or that the reheating temperature is less than about  $10^5 - 10^7$  GeV [15]. In the case that the gravitino is the LSP and the next to lightest supersymmetric particle (NLSP) is the wino, we require the gravitino to be lighter than about 100 MeV [16]. It is particularly problematic when the singlino is the NLSP since its decay to the gravitino is further suppressed, unless the singlino density is strongly diluted by some late time entropy generation. We also note that decaying into a light gravitino,  $m_{3/2} \sim \text{MeV}$ , is not observable on collider time scales since the NLSP is neutral.

Since the squarks are heavy the gluino decays off-shell [10]. Its life-time is very sensitive to  $g_{z'}$  and is given by,

$$\tau_{\tilde{g}} = 4 \times 10^{-16} \text{sec} \left( \frac{m_{\tilde{Q}}}{10^2 \text{ TeV}} \right)^4 \left( \frac{1 \text{ TeV}}{M_3} \right)^5 \propto \frac{1}{g_{z'}^6}. \quad (4)$$

Even though the life-time is long enough for the gluino to hadronize it is too short to result in a displaced vertex.

Since the scalars are heavy, one-loop contributions to most flavor observables (such as  $b \rightarrow s\gamma$ ) are highly suppressed. There are also two loop contributions to EDM and muon  $g - 2$ . However, those are suppressed as compared with the Split SUSY scenario [10] since the Higgsinos are heavy and the singlino-wino mixing is small. The exotic matter in this model is very heavy and does not enter any collider phenomenology.

#### IV. DISCUSSION

In this letter, we discussed the generic feature of supersymmetry breaking dominantly mediated by an extra  $U(1)'$ . We have used a  $U(1)'$  which forbids a  $\mu$  term. Such a requirement gives additional constraints and predicts interesting low energy phenomenology, such as the existence of a light singlino and  $Z'$  in various regions of the parameter space. However,  $Z'$ -mediation is possible in a wider range of  $U(1)'$  models, such as  $U(1)_{B-L}$ . We

expect the hierarchy between the soft scalar masses and the gaugino masses to be generic, although the detailed pattern of soft terms could be quite different. Considering  $Z'$ -mediation in a broader range of models is certainly worth pursuing.

The model presented here does not provide a seesaw mechanism for neutrino mass. However, in a simple variant the  $U(1)'$  symmetry forbids Dirac Yukawa couplings  $Y_\nu H_u L \nu^c$  at the renormalizable level, but allows them to be generated by a higher-dimensional operator [17],

$$W_\nu = c_\nu \frac{S}{M_P} H_u L \nu^c. \quad (5)$$

This naturally yields small Dirac neutrino masses of order  $(0.01 c_\nu)$  eV for  $\langle S \rangle = 100$  TeV.

There are several scenarios for the decays and lifetimes of the heavy exotic particles [18] and for gauge unifica-

tion. These depend on the details of the  $U(1)'$  charge assignments, and will be discussed in [11].

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